

A DARK FORCE FOR BARYONS

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Dark matter à la Occam



lex parsimoniae

Visible sector

Dark sector

THE STANDARD MODEL						
	Fermions			Bosons		
Quarks	<i>u</i> up	<i>c</i> charm	<i>t</i> top	γ photon	Force carriers	
	<i>d</i> down	<i>s</i> strange	<i>b</i> bottom	<i>Z</i> Z boson		
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	<i>W</i> W boson		
	<i>e</i> electron	μ muon	τ tau	<i>g</i> gluon		
			Higgs* boson			

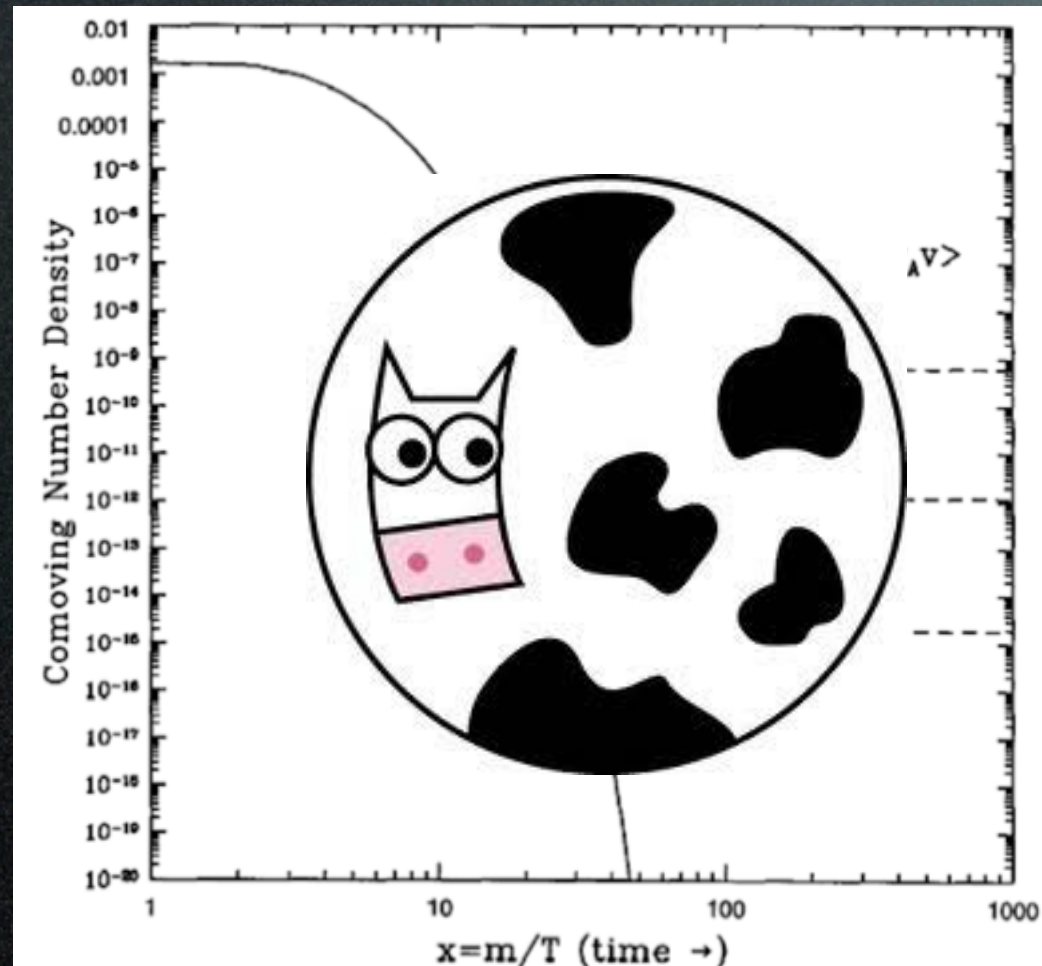
*Yet to be confirmed

Source: AAAS

X

The WIMP miracle

$$\chi\chi \leftrightarrow \bar{f}f$$



= ?

$$\Omega_{DM} h^2 = 0.1 \left(\frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle} \right)$$

What do we really know about DM?

1. Cosmological abundance.
2. It's stable (or at least very long-lived).

Clue #1: WMAP

- ✧ The amounts of dark and visible matter are comparable. WMAP 7 tells us:

$$\Omega_{DM} h^2 = 0.1109 \pm 0.0056$$

$$\Omega_B h^2 = 0.02258^{+0.00057}_{-0.00056}$$

DMB ratio:

$$\frac{\Omega_{DM}}{\Omega_B} \approx 5$$

- ✧ This could be
 1. A remarkable coincidence.
 2. An anthropic selection effect? [Freivogel (2008)]
 3. An indication of an underlying origin.

Enter asymmetric dark matter

- Maybe DM carries a particle anti-particle asymmetry like baryons.
- Earliest attempts made use of EW sphalerons (Nussinov 1985; Barr, Chivukula, Farhi 1990; Kaplan 1992).
- Modern incarnation makes use of higher dimensional operators to transfer the asymmetry (Kaplan, Luty, Zurek 2009).
- ADM models prefer GeV scale masses, but can accommodate weak scale masses (Buckley, Randall 2010), or sub-GeV masses (Falkowski, Ruderman, Volansky 2011).

Will the real model of nature please stand up?

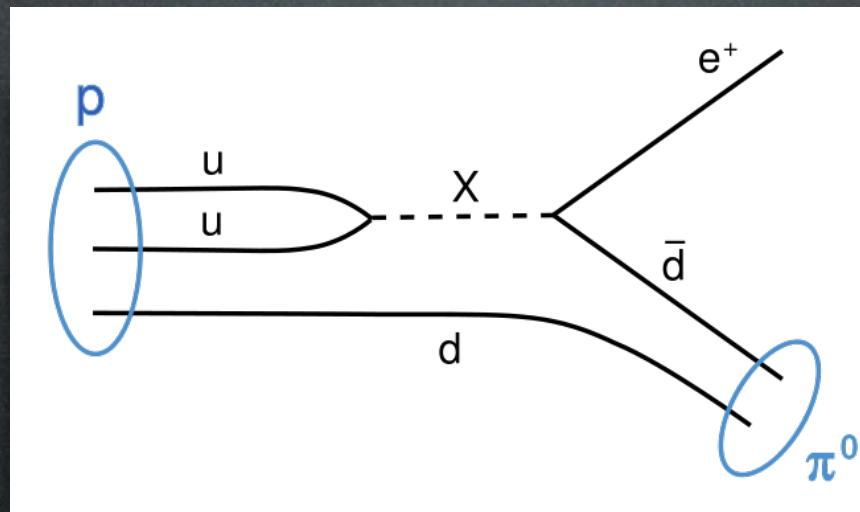
- Darkogenesis? [J. Shelton, K. Zurek (2010)]
- Xogenesis? [M. Buckley, L. Randall (2010)]
- Aidnogenesis? [Blennow, et al. (2010)]
- Hylogenesis? [H. Davoudiasal et al. (2010)]
- Cladogenesis? [R. Allahverdi, B. Dutta, K. Sinha (2011)]
- Pangenesis. [N. Bell, K. Petraki, I.M.S., R. Volkas (2011)]

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BSM physics has a love/hate relationship with the proton

- Often predict an intriguing signal...
 - For example, in SU(5):



The only problem is...

Super Kamiokande says:

The proton is stable.

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo,

The proton is stable

- Why?

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{eff}$$

$$\mathcal{L}_{eff} \subset \frac{QQQL}{\Lambda^2}$$

Baryon number is an
unreasonably good
symmetry

$$p \longrightarrow e^+ \pi^0$$

$$\tau_p > 10^{33} yr$$

$$\Lambda > 10^{15} \text{GeV!}$$

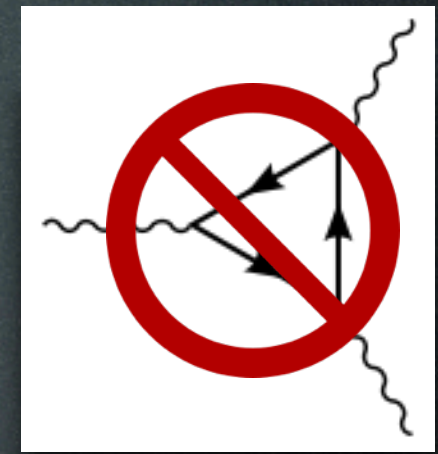
Think globally? Act locally.

- Promote $U(1)_B$ to a *local* gauge symmetry.
- New quarks to cancel anomalies.
- To avoid stable colored particles, introduce new particle X , to facilitate decay.
- X is **automatically** stable.
- Baryogenesis *requires* a DM asymmetry.
- Shared gauge interactions with baryons may facilitate its discovery.

Gauging baryon number

- Ancient examples:
 - Carone and Murayama 1998; Bailey and Davidson 1995; Aranda and Carone 1998.
- More recently:
 - Dulaney, Fileviez-Perez and Wise (2010); Buckley, Fileviez-Perez, Hooper, and Neil (2011).

An anomaly-free model



- New chiral states

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_B$
Q'_i	3	2	$+\frac{1}{6}$	$-\frac{1}{N}$
u'_{ci}	$\bar{3}$	1	$-\frac{2}{3}$	$+\frac{1}{N}$
d'_{ci}	$\bar{3}$	1	$+\frac{1}{3}$	$+\frac{1}{N}$
L'_i	1	2	$-\frac{1}{2}$	0
ν'_{ci}	1	1	0	0
e'_{ci}	1	1	+1	0

N dark generations

- Spontaneously break $U(1)_B$

S^+	1	1	0	$+B(S)$
S^-	1	1	0	$-B(S)$

Not your typical 4th generation

- Gauge symmetry forbids mass mixing.
 - * No tree-level flavor changing processes, decay modes not like conventional 4th gen.
- New quarks carry their own global $U(1)_{B_{q'}}$
 - * The lightest particle in Q' -sector will be stable.

Absence of stable colored particles

- Exotic quarks must decay...

$$\mathcal{L} \supset \frac{u_c d_c d'_c X}{\Lambda} \quad \overline{q'} \rightarrow qqX$$

- Turning off gauged baryon number, we see three accidental symmetries

$$Q \rightarrow e^{i\theta_q} Q$$

$$Q' \rightarrow e^{i\theta_{q'}} Q'$$

$$S \rightarrow e^{i\theta_S} S$$

gauge B

$$\implies B = B_q + B_{q'} + B_S$$

Absence of stable colored particles

- Exotic quarks must decay...

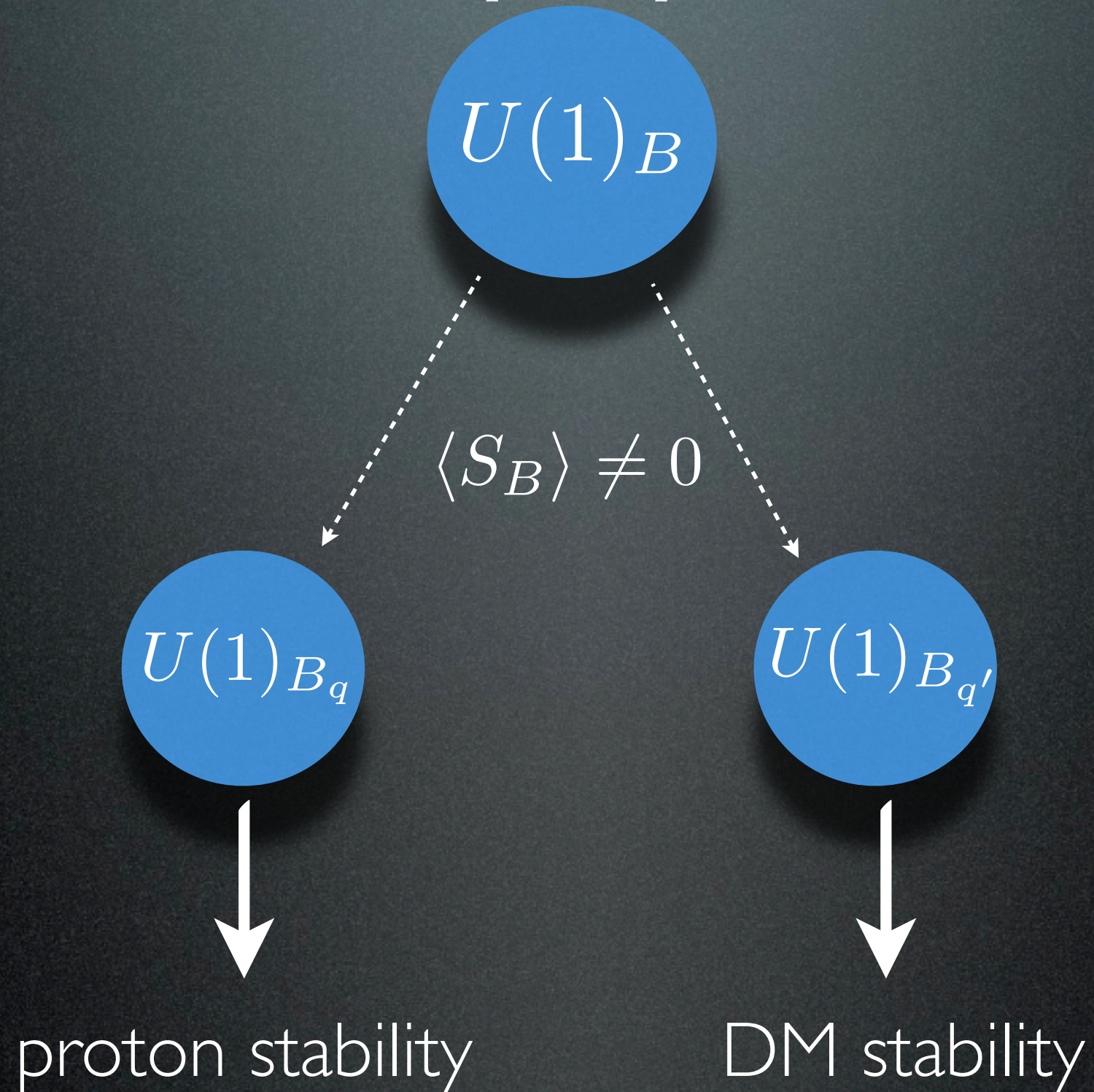
Introduce: $X^\pm \sim \left(1, 1, 0, \pm \left(\frac{2}{3} - \frac{1}{N}\right)\right)$

$$\mathcal{L} \supset \frac{u_c d_c d'_c X}{\Lambda} \quad \overline{q'} \rightarrow qqX$$

Decay operator \leftrightarrow asymmetry transfer operator

Spontaneous breaking

$$B = B_q + B_{q'} + B_S$$



STABILITY OF MATTER

- What about proton/DM decay at the non-renormalizable level?

$$\mathcal{O}_{bad} \sim X P^\delta S^\epsilon L^\nu \mathcal{O}$$

$$X \rightarrow \delta P + \epsilon S + \nu L + \dots$$

$$\mathcal{O}_{worse} \sim p L^\alpha X^\beta S^\gamma \mathcal{O}'$$

$$p \rightarrow \alpha L + \beta X + \gamma S + \dots$$

Simple example: $m_X > m_p$

- Proton stability: $B(S) \in \mathbb{Z}, |B(S)| > 1$
- DM stability: $B(X) = \text{fraction}.$

Baryogenesis implies a DM asymmetry

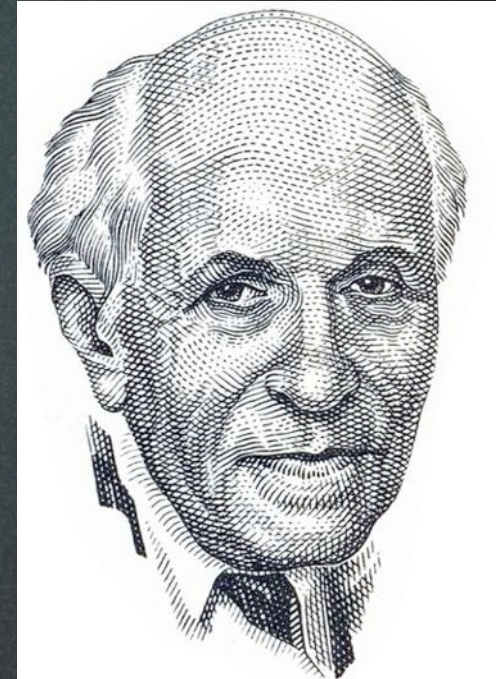
- The only global symmetry is a non-anomalous $U(1)_D$:

$$D = B_q + B_{q'}$$

$$n_B \neq n_{\bar{B}} \Rightarrow n_X \neq n_{\bar{X}}$$

- Unlike conventional ADM, the asymmetries are co-generated.
- Recent work by: Bell, Petraki, IMS, Volkas [1105.3730]; Cheung and Zurek [1105.4612].

Asymmetries are generic



A. Sakharov

- CP violation.
- $U(1)$ violation; gravity doesn't respect them.
- Out of equilibrium.

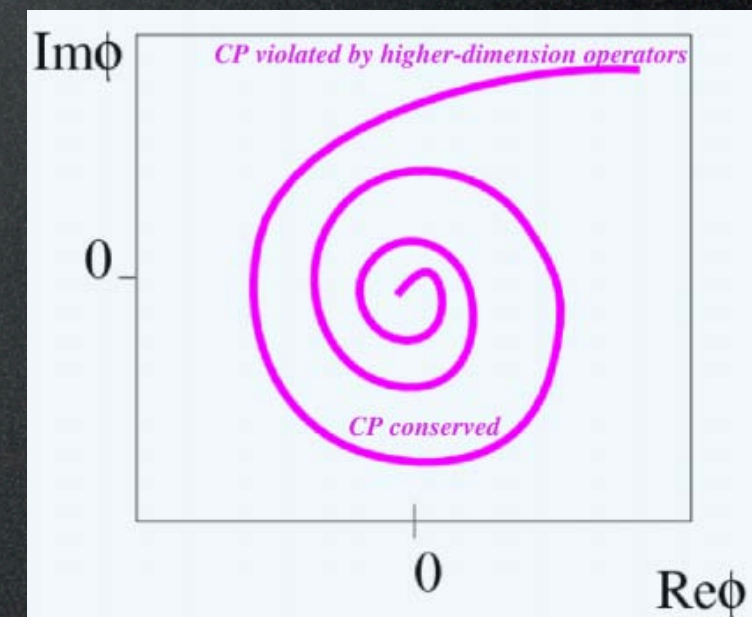
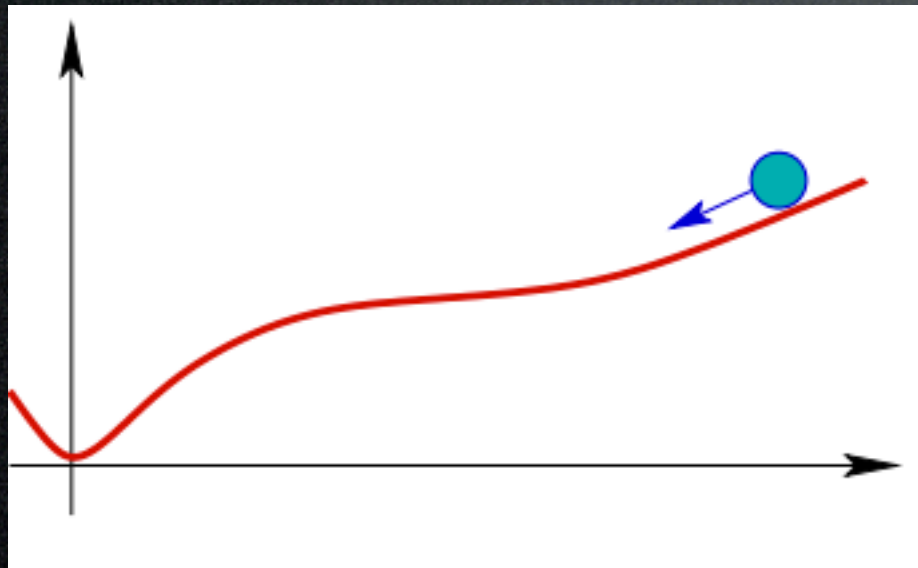
Super example: Affleck-Dine

- Affleck-Dine simplified:

$$n_B = \dot{\theta} |\phi|^2$$

- Acquire a large VEV.
- Kick the field in the phase direction.

Affleck, Dine (1985); Dine, Randall, Thomas (1995).



Symmetries \leftrightarrow chemical potentials

Harvey & Turner (1992)

- Universe is EM neutral.
- EW Sphalerons are active above T_{EW} .
- Transfer operator
- W and Higgs exchange.


Solve for:

$$\mu_u, \mu_d, \mu_l, \mu_\nu, \mu_W, \mu_X, \mu_{q'}$$

Similar asymmetries yield similar masses

Generically: $\frac{\eta_B}{\eta_X} = \mathcal{O}(1)$ For the model introduced above: $\frac{\eta_B}{\eta_X} \lesssim 6$

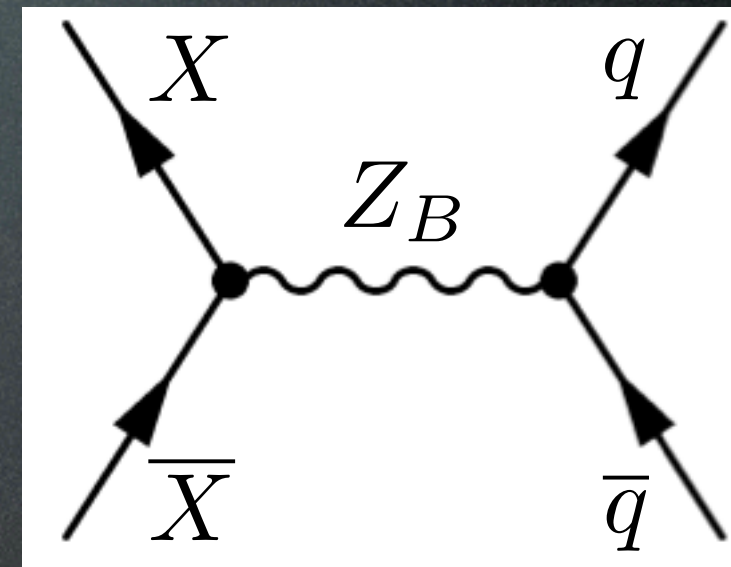
$$\frac{m_X}{m_p} \left(\frac{n_+ - n_-}{n_+ + n_-} \right) = \frac{\eta_B}{\eta_X} \frac{\Omega_{DM}}{\Omega_B}$$

 $m_X \lesssim 30 \text{ GeV}$

Light DM is generic in ADM models.

Abundance via annihilation

Minimal assumption:
annihilation dominantly
from s-channel Z_B



$$\begin{aligned} \langle \sigma_{ann} v \rangle &= \sum_f \frac{N_c}{2\pi} m_X^2 \left(\frac{g_B^2}{m_B^2} \frac{q_X}{3} \right)^2 \frac{\left(2 + \frac{m_f^2}{m_X^2} \right)}{\left(1 - \frac{4m_X^2}{m_B^2} \right)^2 + \frac{\Gamma_B^2}{m_B^2}} \sqrt{1 - \frac{m_f^2}{m_X^2}} \\ &\simeq \frac{N_f}{3\pi} m_X^2 \left(q_X \frac{g_B^2}{m_B^2} \right)^2 \left[\left(1 - \frac{4m_X^2}{m_B^2} \right)^2 + \frac{\Gamma_B^2}{m_B^2} \right]^{-1} \end{aligned}$$

Asymmetry impact on abundance

from M. Graesser, I.MS., L. Vecchi,
arXiv:1103.2771

$$X\bar{X} \leftrightarrow f\bar{f}$$

As long as an asymmetry exists prior to FO, must solve coupled Boltzmann eqs. for abundances.

Large $\langle\sigma v\rangle$

$$\Omega_{DM} \propto \eta$$

Small $\langle\sigma v\rangle$

$$\Omega_{DM} \propto \langle\sigma v\rangle^{-1}$$

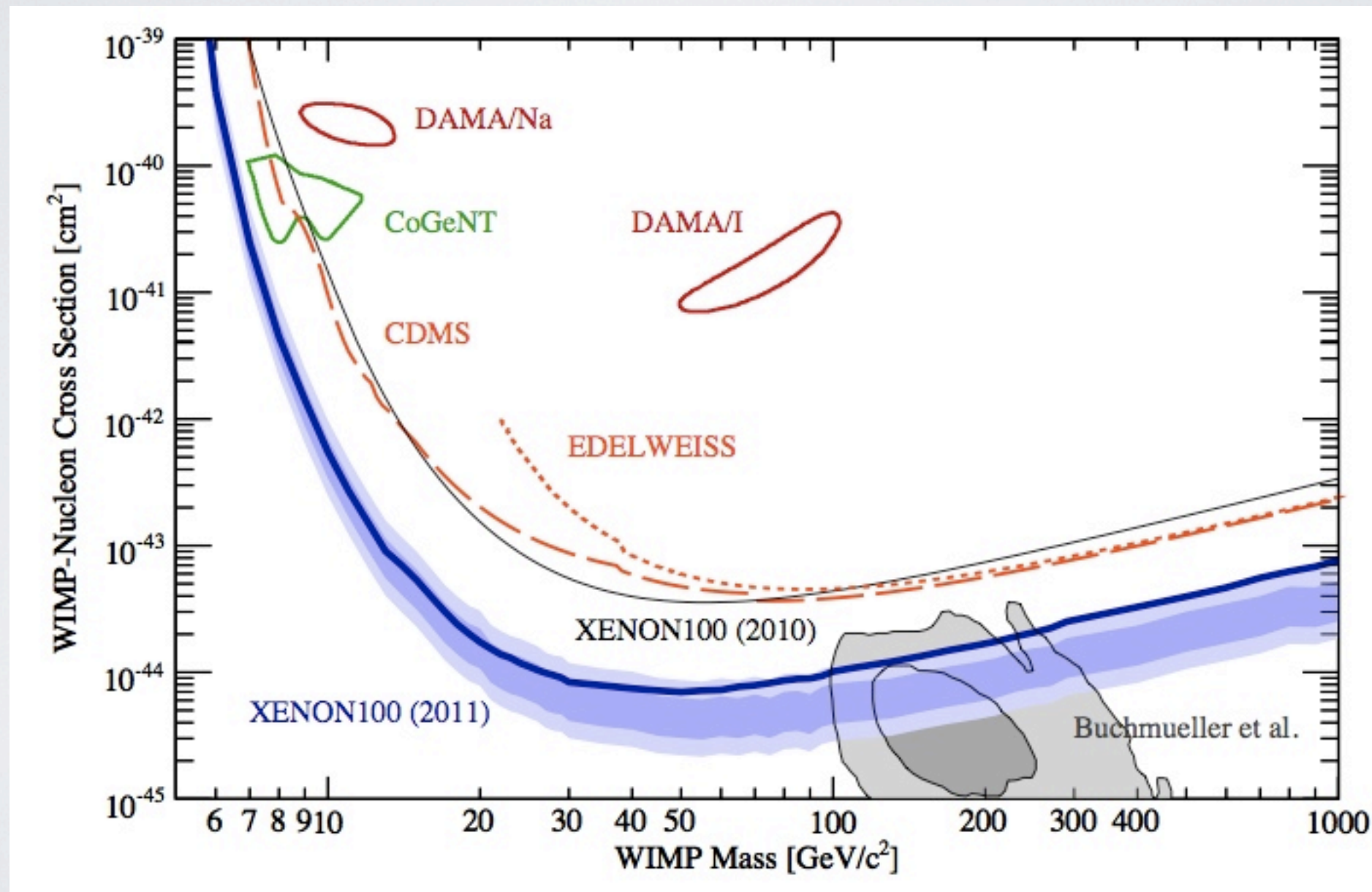
More generally:

$$\Omega_{DM} = f(\eta, \langle\sigma v\rangle, m)$$

$$\langle\sigma v\rangle \geq 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$$

ADM can have WIMP
sized cross sections!

DIRECT DETECTION BOUNDS



RECOIL SPECTRUM

$$\frac{dR}{dE_R} = \frac{N_T \rho_\odot}{m_X} \int_{|\vec{v}| > v_{min}} d^3v \, v f(\vec{v}, \vec{v}_\oplus) \frac{d\sigma}{dE_R}$$

↑ astrophysics/N-body
↓ kinematics
↓ particle physics

- Velocity distribution must be consistent with NFW:

$$f(v) \propto \left[\exp \left(\frac{v_{esc}^2 - v^2}{k v_0^2} \right) - 1 \right]^k$$

[Lisanti, Strigari, Wacker, Wechsler (2010)]

- Non-trivial velocity/momentum dependence in cross section in some models.

RECOIL SPECTRUM

VECTOR CASE:

$$D^\mu X = \partial^\mu X + ig_B (q_V + \cancel{q_A} \gamma^5) Z_B^\mu X$$

$$\frac{d\sigma}{dE_R} = \frac{m_N A^2}{2\pi v^2} \left(\frac{q_V g_B^2}{m_B^2} \right)^2 F^2(E_R) \quad \text{DD imposes: } m_X \lesssim \text{few GeV}$$

AXIAL CASE:

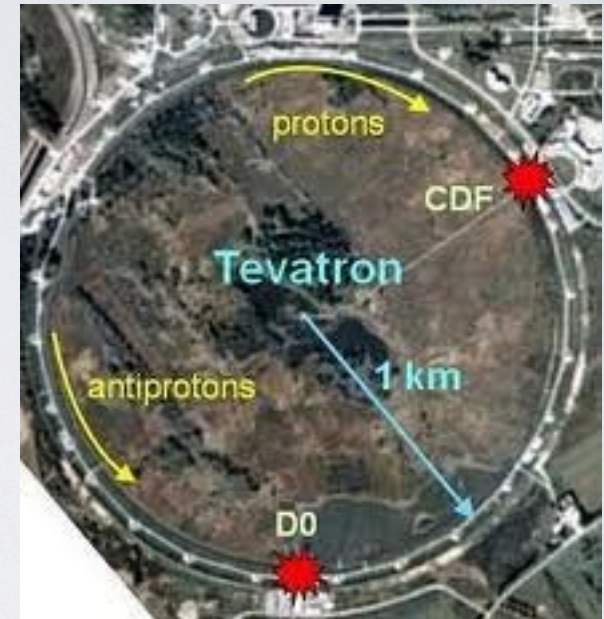
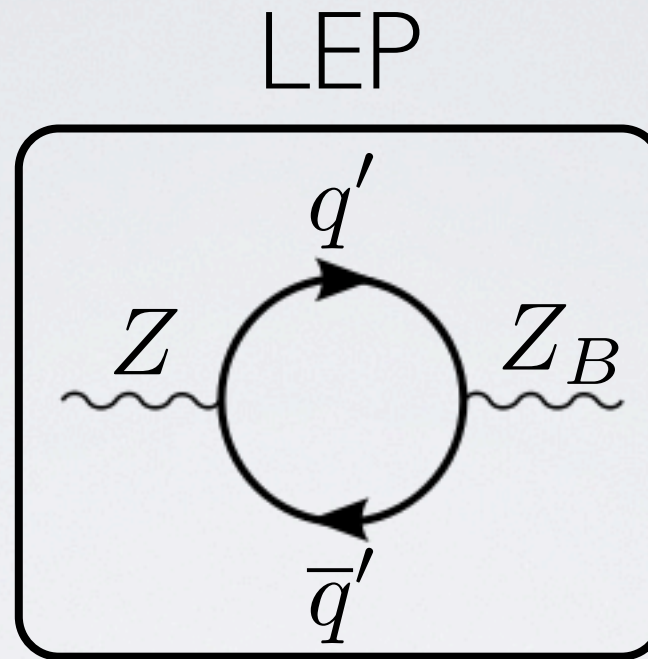
$$D^\mu X = \partial^\mu X + ig_B (\cancel{q_V} + q_A \gamma^5) Z_B^\mu X$$

$$\frac{d\sigma}{dE_R} = \frac{m_N A^2}{8\pi v^2} \left(\frac{q_A g_B^2}{m_B^2} \right)^2 [Av^2 + Bq^2] F^2(E_R)$$

Always $\gtrsim 2$
below DD bounds.

BARYONIC DARK FORCES AND COLLIDERS

A TRIFECTA OF EXPERIMENTS



- BaBar: invisible/hadronic upsilon decays.
- LEP: hadronic width of the Z boson.
- Tevatron: monojets + missing energy.

B-FACTORY CONSTRAINTS

If $m_X \lesssim m_\Upsilon/2$, the upsilon can decay to DM.

$$\Upsilon(1S) \rightarrow Z_B \rightarrow \bar{X}X$$

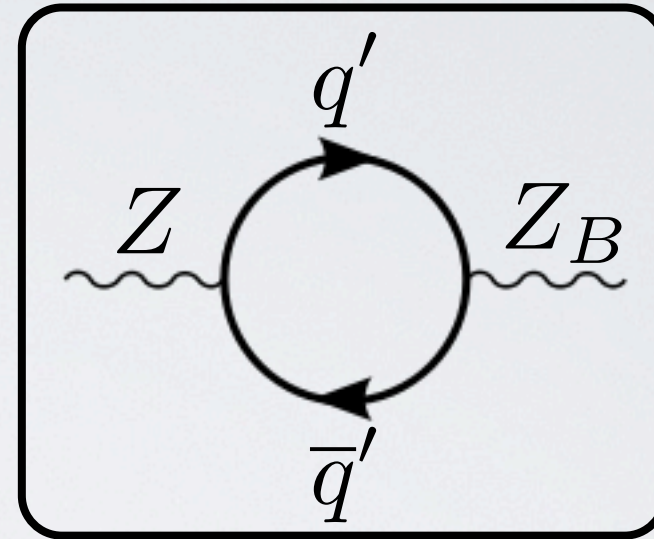
BaBar constrains:

$$\mathcal{BR}(\Upsilon(1S) \rightarrow \text{“invisible”}) < 3 \times 10^{-4}$$

$$\frac{\mathcal{BR}(\Upsilon(1S) \rightarrow \text{“invisible”})}{\mathcal{BR}(\Upsilon(1S) \rightarrow \mu^+\mu^-)} = (q_V^2 + q_A^2) \left[\frac{g_B^2}{e^2} \frac{m_\Upsilon^2}{m_B^2 - m_\Upsilon^2} \right]^2 < 1.2 \times 10^{-2}$$

BOUNDING A BARYONIC GAUGE BOSON WITH LEPTONS

Kinetic mixing:



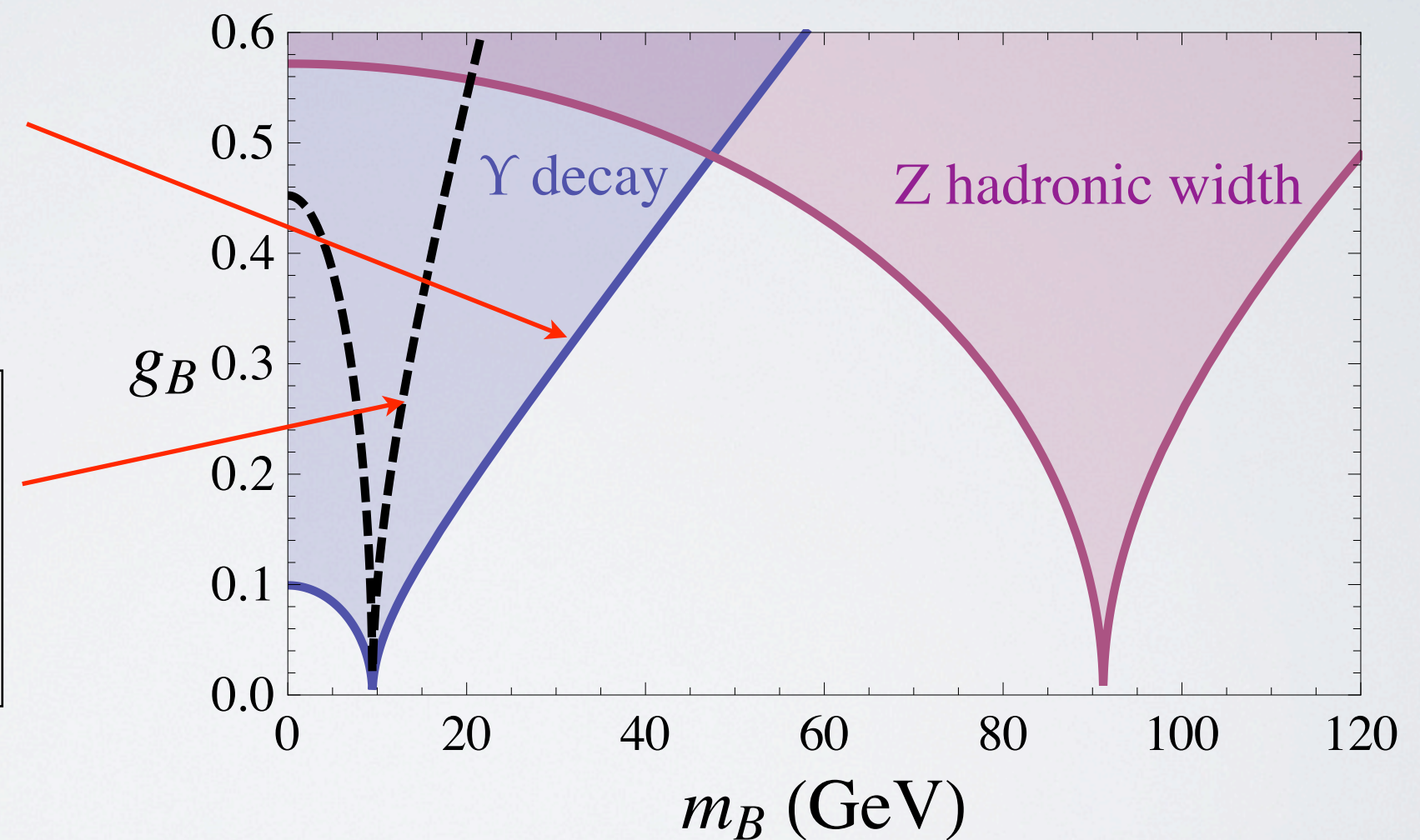
$$\mathcal{L}_{kin} = -\frac{1}{4} (Z_B^{\mu\nu} Z_B^{\mu\nu} - 2c_Z s_W Z_B^{\mu\nu} Z^{\mu\nu} + 2c_\gamma c_W Z_B^{\mu\nu} A^{\mu\nu})$$

$$\frac{\Delta\Gamma_{had}}{\Gamma_{had}} \approx 1.193 \frac{g_B}{\sqrt{4\pi}} c_Z(m_Z) \frac{m_Z^2}{m_Z^2 - m_B^2} \lesssim \pm 1.1 \times 10^{-3}$$

Experimental constraints: LEP + B-factories

$m_X \lesssim m_\Upsilon/2$
invisible
upsilon width

$m_X \gtrsim m_\Upsilon/2$
hadronic
upsilon width



Monojets at the Tevatron

$$p\bar{p} \rightarrow \cancel{E}_T + j$$

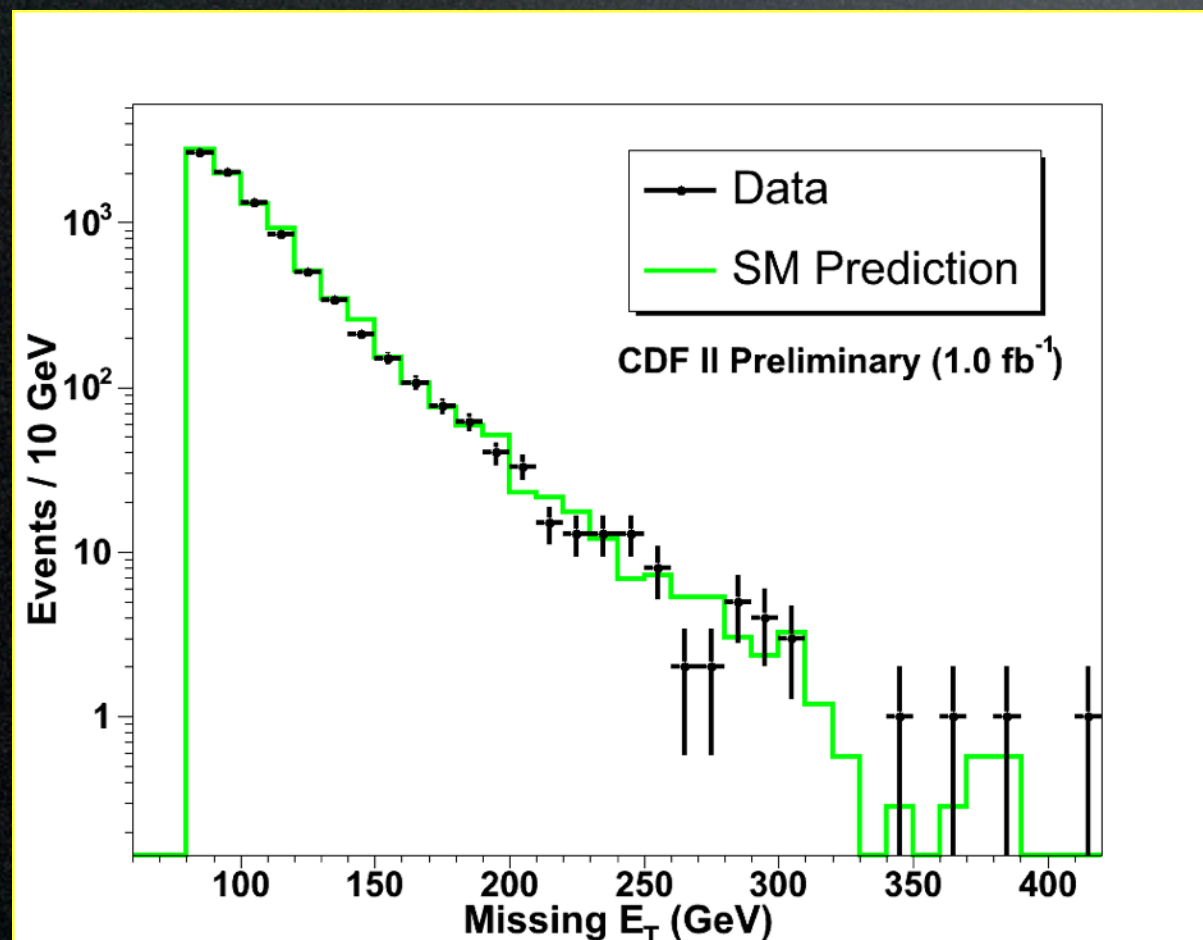
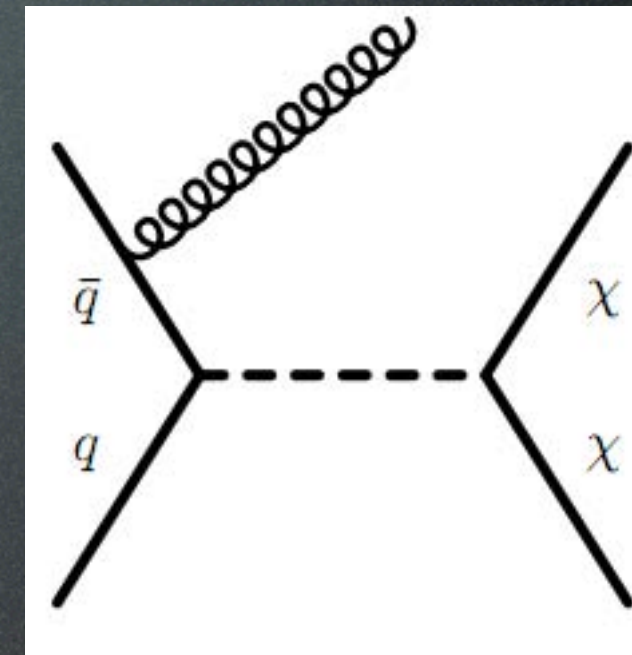
$\sim 1\text{fb}^{-1}$ analyzed data

$$\cancel{E}_T > 80 \text{ GeV}$$

$$p_T(j_1) > 80 \text{ GeV}$$

$$p_T(j_2) < 30 \text{ GeV}$$

$$p_T(j_3) < 20 \text{ GeV}$$



8449 events seen

See also: Bai, Fox, and Harnik (2010);
Goodman et al. (2010)

DARK FORCES AT THE TEVATRON

$$D^\mu X = \partial^\mu X + ig_B (q_V + \cancel{q_A} \gamma^5) Z_B^\mu X$$

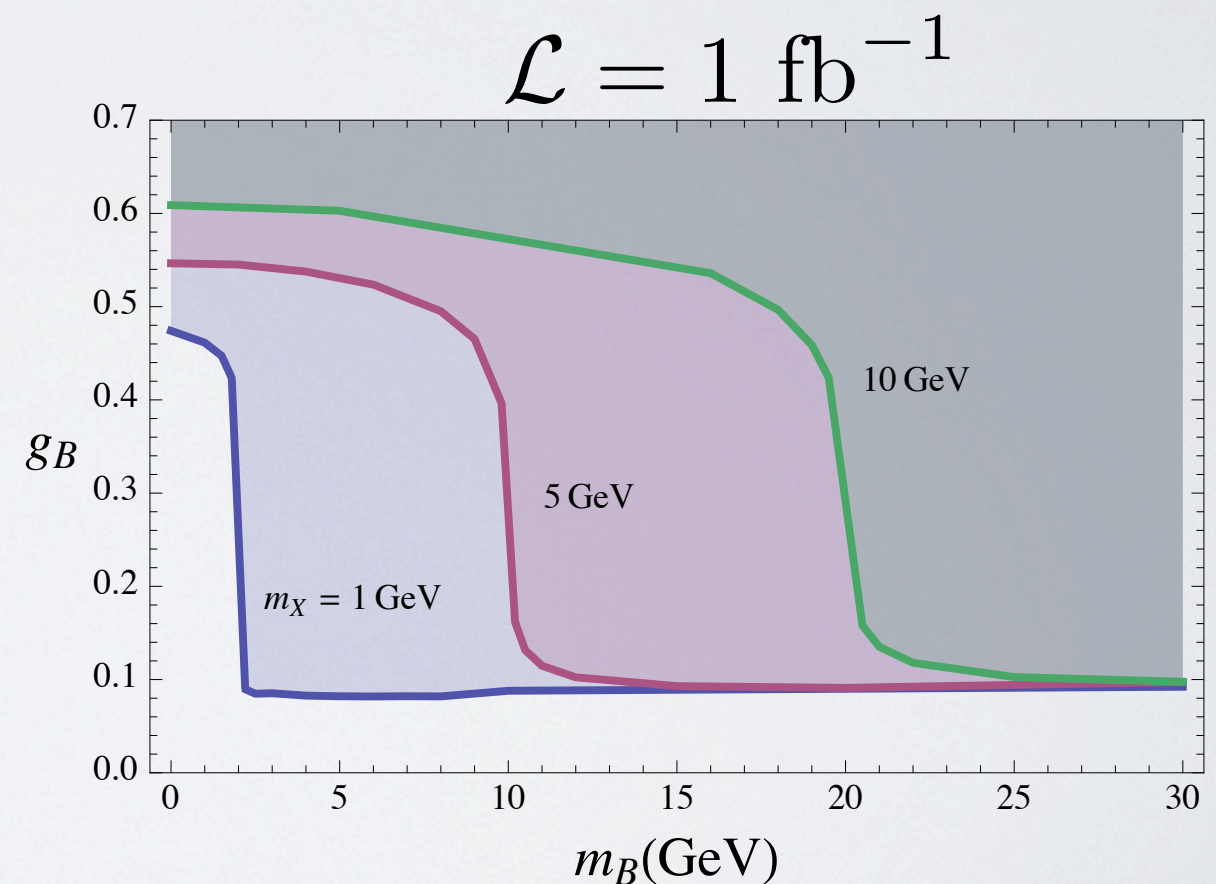
8449 events w/ 1 fb^{-1}

SM: 8662 ± 332

90 C.L. $S < 330$ events

-Madgraph/Madevent to
simulate parton-level signal.

-Pythia for ISR/FSR/
hadronization and analysis.

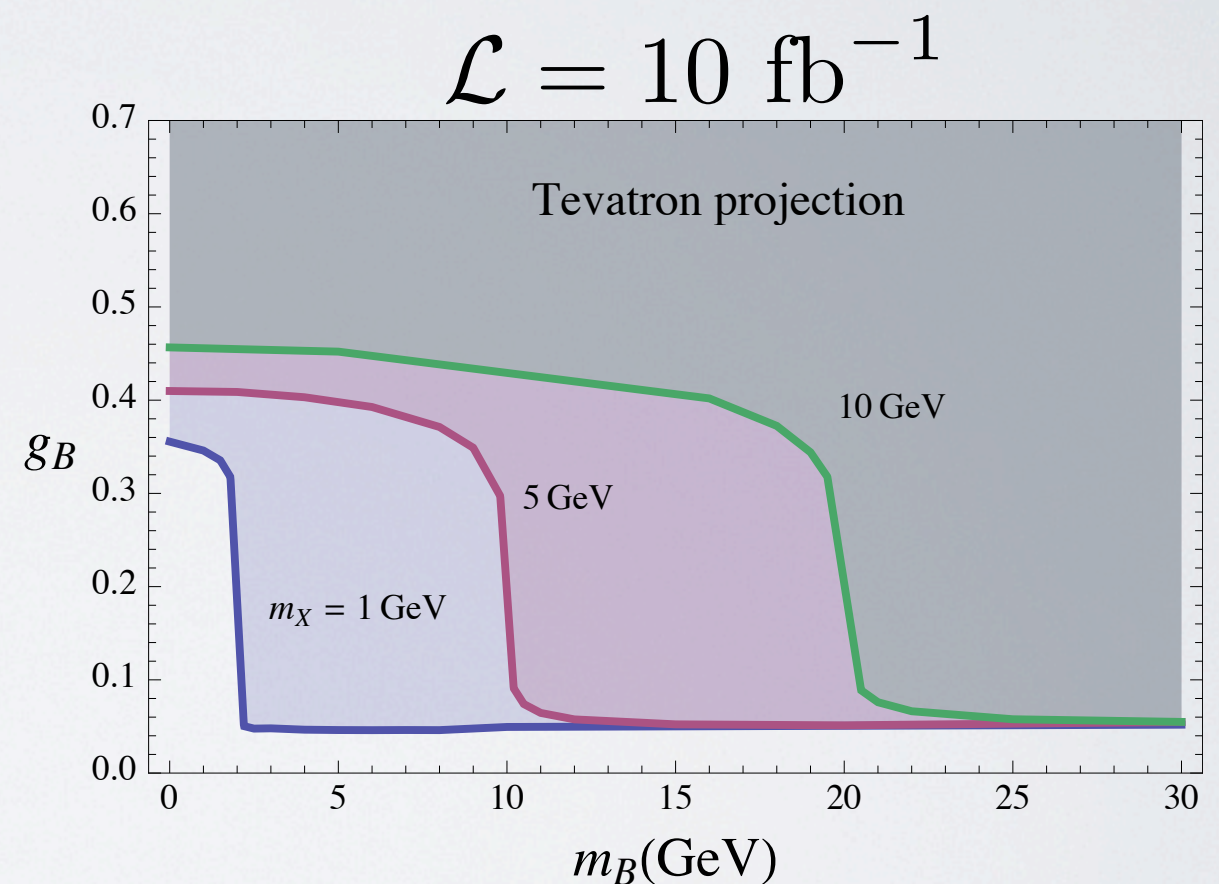


DARK FORCES AT THE TEVATRON

8449 events w/ 1fb^{-1}
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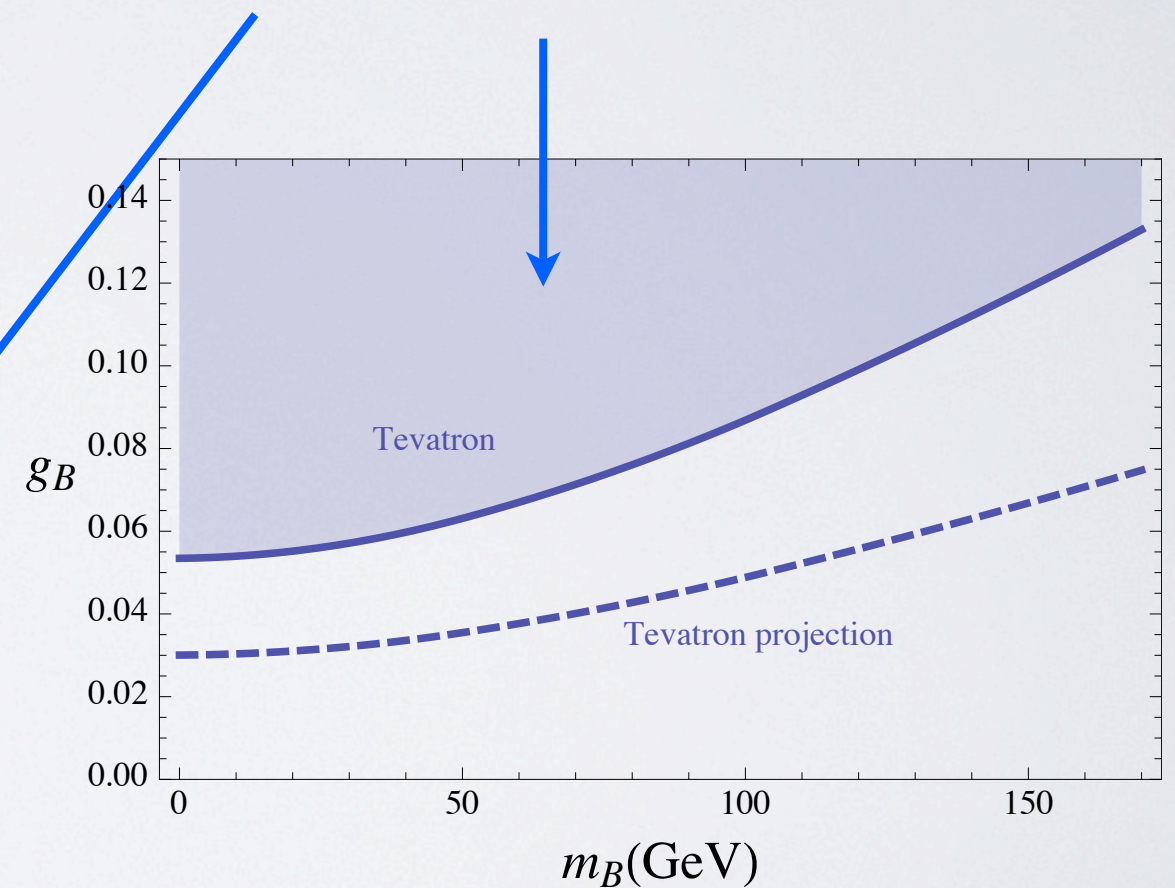
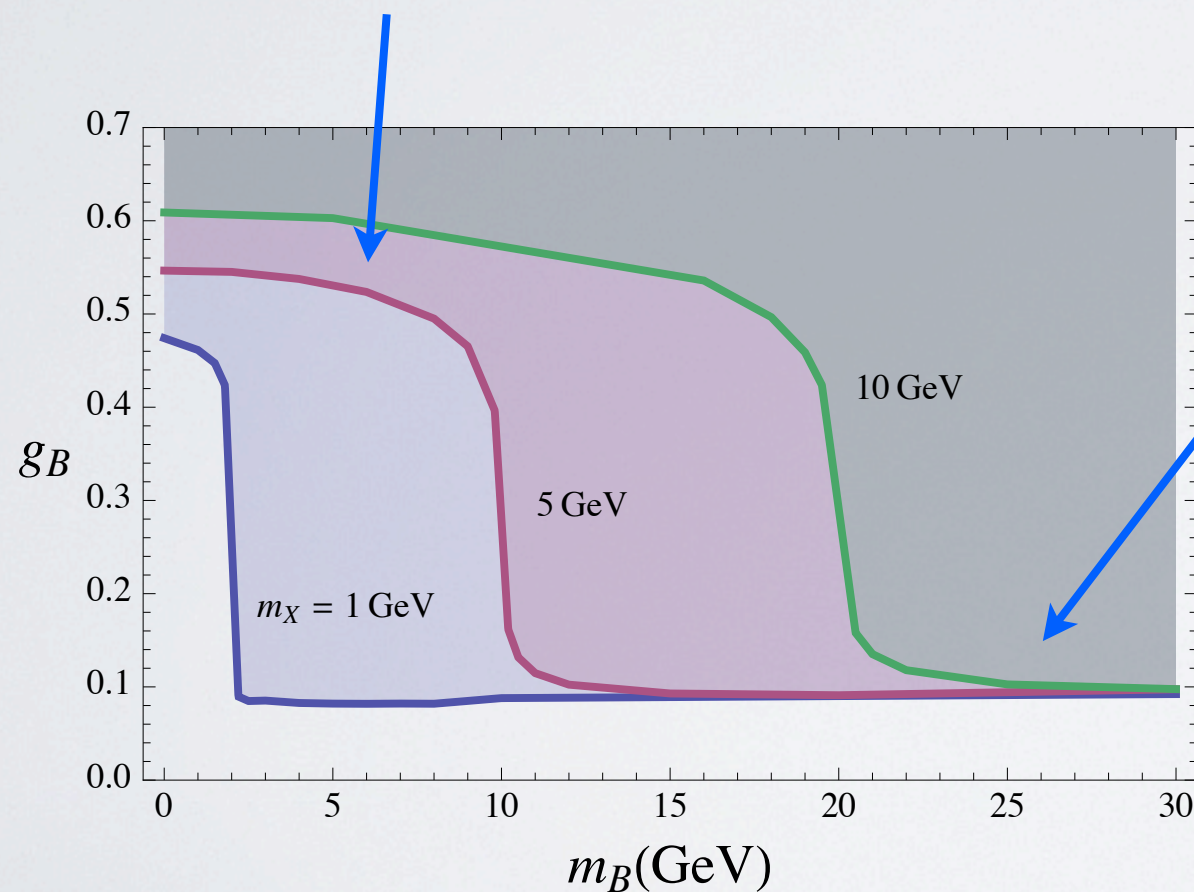
DARK FORCES AT THE TEVATRON

off-shell ZB production

$$\sigma \propto g_B^4$$

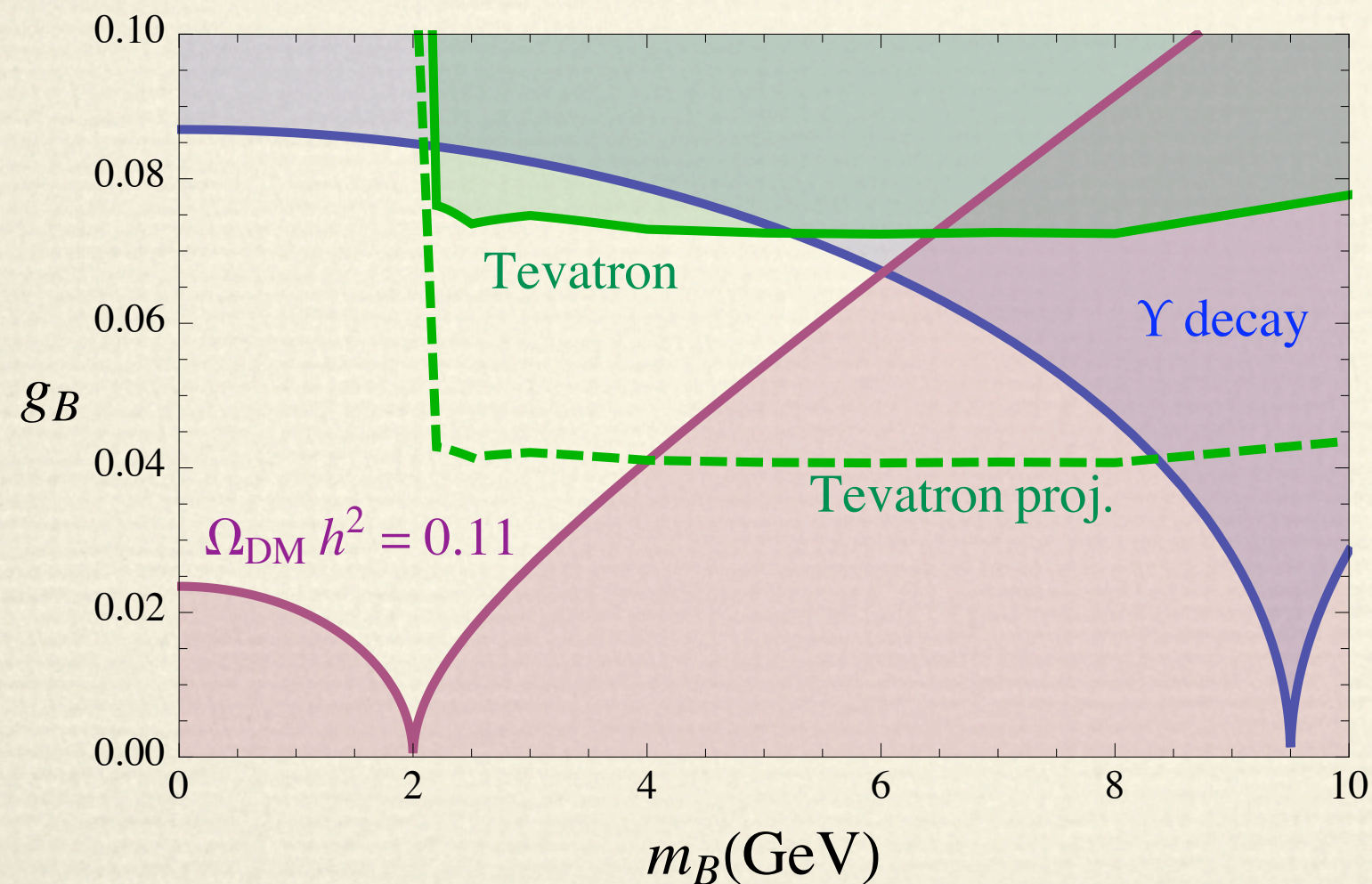
on-shell ZB production

$$\sigma \propto g_B^2$$



Combined constraints: vector case

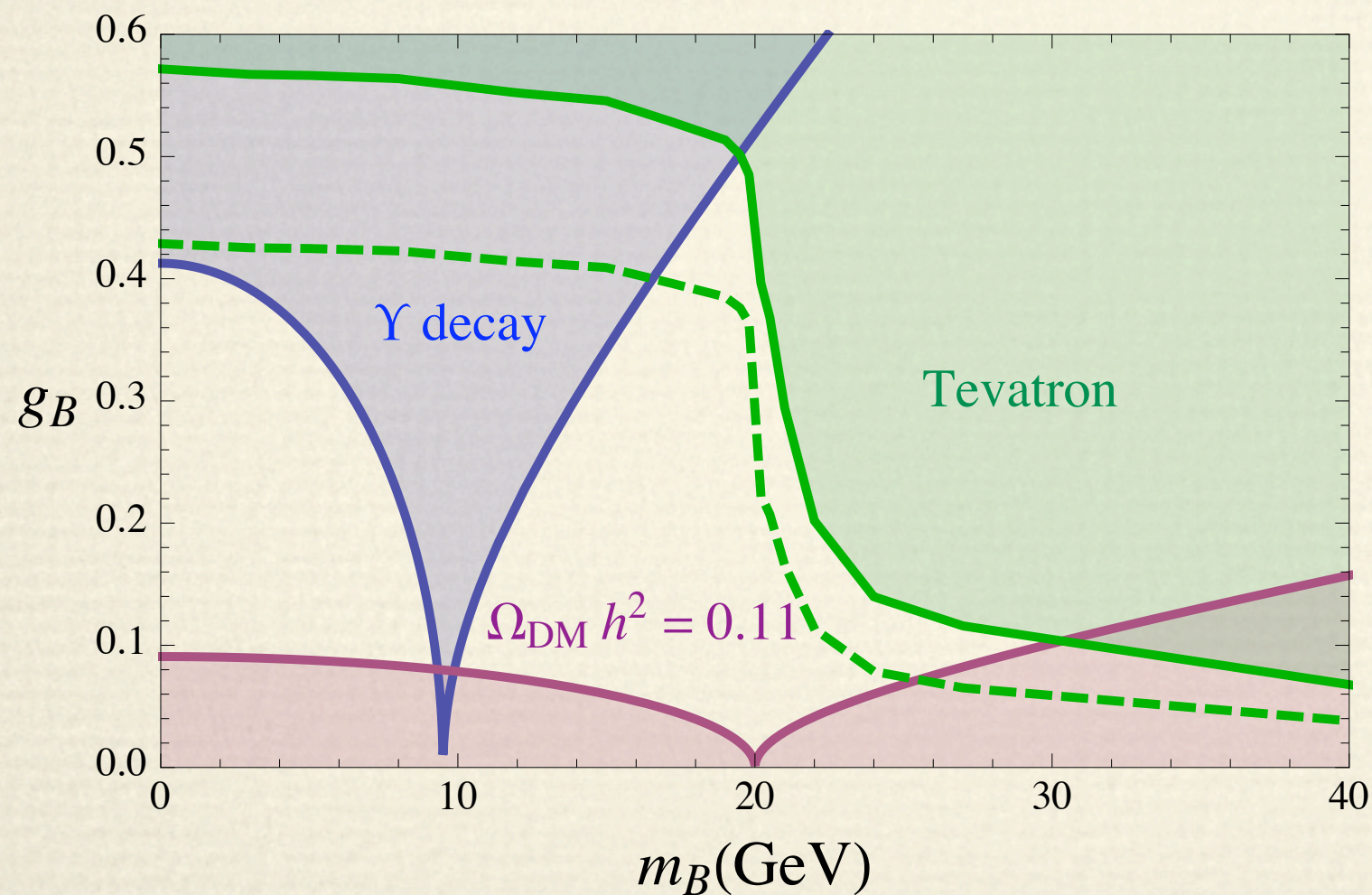
$$D^\mu X = \partial^\mu X + ig_B (q_V + \cancel{q_A \gamma^5}^0) Z_B^\mu X$$



$$m_{DM} = 1 \text{ GeV}$$

Combined constraints: axial case

$$D^\mu X = \partial^\mu X + ig_B (\cancel{q_V} + q_A \gamma^5) Z_B^\mu X$$



$$m_{DM} = 10 \text{ GeV}$$

CONCLUSIONS

- Gauged baryon number saves the proton + automatic DM candidate.
- Co-generation of dark and visible asymmetries via Affleck-Dine.
- Consistent with bounds from B-factories, LEP, mono-jet Tevatron searches, and direct detection for:
 - GeV-scale DM with a GeV-scale mediator.